Table 5. Transaction Summary

ID	Function	Transaction	Downlink (bits)	Uplink (bits)	Total Size (bits)	Data Rate (bits/sec)
1	Electronic Toll Collection	Toll Payment	196	240	436	466453
2	Parking Payments	Obtain Parking Fee	196	80	276	18817
3	Parking Payments	Parking Payment	196	240	436	18433
4	Drive-Thru Payments	Drive-Thru Payment	508	232	740	18433
5	In-Vehicle Signing & Traffic Information	Sign Data	208	175	383	580707
6	CVO International Border Clearance	Border Clearance	219	200	419	408699
7	CVO International Border Clearance	Lock Tag Data	56	109	165	462730
8	CVO Electronic Clearance	Screening	398	1042	1440	390929
9	CVO Safety Inspection	Safety Inspection	244	151	395	18083
10	CVO Fleet & Freight Management	Safety Data Upload	56	162	218	216682
11	CVO Fleet & Freight Management	Access Control	144	175	319	18247
12	CVO Fleet & Freight Management	Driver's Daily Log Upload	72	180	252	12646
13	Off-Line Verification & Electronic License Plate	Registration Data Upload	392	712	1104	49188
14	Emergency Vehicle Signal Preemption	Signal Preemption	176	88	264	580707
15	Transit Vehicle Signal Priority	Signal Priority Request	176	88	264	580707
16	Transit Vehicle Data Transfer	Transit Fleet Status	760	72	832	26093
17	Transit Vehicle Data Transfer	Traveler Information	2456	2456	4912	18265
18	Transit Vehicle Data Transfer	Fare Enforcement	160	74264	74424	132699
19	Transit Vehicle Data Transfer	Transit Vehicle Conditions	72	476	548	12646
20	Transit Vehicle Data Transfer	Transit Vehicle Passenger And Use Data	72	2944	3016	19872
21	Transit Vehicle Data Transfer	Driver Instructions	9272	0	9272	32252
22	Transit Vehicle Data Transfer	Advance Payment For Services	448	1288	1736	28906
23	Transit Vehicle Data Transfer	Update The In-Vehicle Kiosk	4915808	0	4915808	534409
24	Transit Vehicle Data Transfer	Fare Payment (Credit Card)	648	64	712	18065
25	Transit Vehicle Data Transfer	Fare Payment (SMART Card)	712	72	784	24462
26	Automated Highway System to Vehicle Communications	AHS Vehicle Data	72	1241	1313	23507
27	Automated Highway System to Vehicle Communications	AHS Control Data Update	4224	205	4429	577546
28	Automated Highway System to Vehicle Communications	AHS Check Response	4225	205	4430	577546
29	Automated Highway System to Vehicle Communications	Speed And Headway	72	110	182	406495
30	Traffic Network Performance Monitoring	Vehicle Probe Data	80	193	273	406495
31	Intersection Collision Avoidance	Intersection Status	188	193	381	580707

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The largest data rate estimated from the proposed requirements is 580707 bps. Typical upper level data rates supported by DSRC equipment currently manufactured ranges from 500 to 600 kbps. A data rate requirement of 600 kbps is selected because it will meet the estimated data rate forecast.

4.2 Channel Bandwidth Requirement

The bandwidth required for DSRC is affected by a number of factors including data rate, modulation type, modulation rate, encoding scheme, difference frequencies, output power, antenna separation (or installation density), propagation characteristics, system out-of-channel emissions requirements, and FCC out-of-band emissions requirements. The primary constituent of the total bandwidth needed is the necessary bandwidth, that amount used to transmit the signal with the quality required, and the secondary factor is the bandwidth needed to allow the amplitude of the harmonics to decrease below the system out-of-channel and FCC out-of-band emissions requirements. Having determined the data rate we can now compute the channel bandwidth required for the DSRC applications.

Currently, several different air interface specifications are used to perform DSRC communications in the 5.8 ISM band - mostly in European and Asian countries. The European Prestandard, CEN TC278, DSRC Physical Layer using Microwave at 5.8 GHz, is the 5.8 GHz air interface specification that contains the most detail at this time. However, the developing Draft ASTM Standard for Dedicated, Short Range, Two-Way Vehicle to Roadside Communications Equipment is adaptable to 5.8 GHz and has been tested in Asia operating in this mode. Neither, however, fully supports all the DSRC applications expected to be implemented. The European Prestandard supports multiple channels and up to 50-foot (15-meter) ranges, and equipment based on the draft ASTM standard supports one-channel operation and more than 100-foot (30-meter) ranges. Multiple channels and more than 100-foot (30-meter) ranges will be needed to encompass all the likely applications discussed here. Therefore, the bandwidth determination should be based on an expected combination of operating characteristics between the two specifications but mostly on the European Prestandard.

The required bandwidth was determined by performing an emulation of the expected transmission characteristics and plotting a spectral diagram of the results (See Appendix C, Spectrum Requirements for a Dedicated Short Range Communications (DSRC) Channel). The calculations included the European prestandard operating characteristics but the data rate was moved up to 600 kbps and the subcarrier frequencies were moved to 1800 kHz and 2400 kHz to accommodate the higher data rate. The emulation showed that the 600 kbps data rate could be transmitted within 6 MHz of bandwidth using baseband signal shaping and filtering. In addition, it is also possible to transmit the 600 kbps in 6 MHz using the ASTM draft standard. Since one option in the ASTM draft standard uses ASK for both the downlink and uplink the FCC formula below can be used to compute the minimum necessary bandwidth directly:

$B_n = KB$ for two-level amplitude modulation [8]

In the above formula, K is a constant with value between 3 for a non-fading channel to 5 for a fading channel, and B is the modulation rate in baud. We use the downlink modulation method assumptions listed previously (ASK with Manchester encoding) and a data rate of 600 kbps. Manchester encoding causes the modulation rate to vary depending upon the exact sequence of information bits. The highest rate occurs when there is a contiguous sequence of "1" or "0" bits; during such a situation the modulation rate would be twice the data rate. Therefore, B = 1200 kbps. The channel characteristics for DSRC are closest to a non-fading channel, due to the short ranges involved. As a consequence of these assumptions, Bn = 3.6 MHz. However, we still need to account for the harmonics and out-of-channel emissions limits.

Of concern when allocating spectrum for DSRC systems are frequency separation and frequency reuse. The assigned channel bandwidth should allow multiple data transmissions with the desired accuracy at different frequencies so that the transmissions do not interfere with each other and do not violate the out-of-band emissions requirements. The bandwidth for current DSRC equipment is generally constrained by the FCC requirement on the LMS band to reduce out-of-band signal levels by 55 + 10 log(P) dB, where P is the effective power of the transmitter. Hence, the channel bandwidth would be set as twice the frequency offset at which the transmitted signal spectrum was 65 dB below that of the center frequency (assuming an Effective Isotropic Radiated Power (EIRP) of 10 Watts). In an ideal world, we would build a filter which completely eliminated everything outside the necessary bandwidth. Of course, that is not possible and we must compromise. For example, an 8 pole filter allowing 3 dB of passband ripple achieves a 65 dB isolation at a bandwidth which is 1.56 times the necessary bandwidth. Simpler (fewer pole) filters would require higher ratios, resulting in larger channel bandwidths. The 8 pole filter offers a reasonably good tradeoff between complexity (synonymous with cost) and bandwidth needed to achieve required isolation , and results in a channel bandwidth of 5.616 MHz. To allow for some drift of the center frequency and normal aging and degradation of components, it seems prudent that 6 MHz should be the bandwidth allowed for each channel.

Although the data rate required could be accomplished in less bandwidth with more complicated modulation schemes, the less complex schemes are used to maintain the lowest tag cost possible. Currently, tags cost between 20 and 100 dollars. Adding signal processing capability to the tag would significantly increase the cost. Because the tag will be distributed to hundreds of thousands or millions of vehicles, any increase in tag cost will have a large economic impact on the system deployment. Therefore, after careful evaluation of the implementation characteristics and deployment, the required bandwidth was determined to be 8 channels of 6 MHz each, or 48 MHz total. So, the LMS band, considering the bandwidth requirement and the other developing users, will be insufficient to support all of the DSRC applications previously discussed. Another band is needed to support the DSRC requirements.

5.0 ANALYSIS OF DSRC COMMUNICATION CHARACTERISTICS

5.1 Current and Proposed Radio Frequency Spectrum Allocation

Now we must determine the frequency range in which to request the allocation of the 48 MHz of bandwidth needed to implement all the functions of ITS DSRC. ETC installations make up most of the DSRC operations currently deployed and operate as Location and Monitoring Service (LMS) systems in the 902 to 928 MHz band under the Transportation Infrastructure Radio Services (TIRS) category—CFR, title 47, Part 90 [8]. However, the Federal Communications Commission (FCC) has allocated this frequency range for use by other types of equipment as well. The band in which LMS operates is assigned on a hierarchical basis as follows:

- Government radiolocation systems and industrial, scientific, and medical (ISM) equipment;
- Government fixed and mobile operations and LMS;
- Amateur radio service licensees; and
- Part 15 devices (*e.g.*, remote meter readers, wireless local area networks, wireless security systems, portable telephones).

However, only two 6 MHz channels can be allocated to ITS functions in this band. In addition, many communications products are being developed for use in this band, and these may interfere with the operation of DSRC equipment at some point in the future. So, considering the bandwidth requirement and the developing other users, the 902 to 928 band may be insufficient to support the large number of DSRC applications to be implemented. To meet the projected need for increased bandwidth, other areas of the spectrum have been considered. Although it is not currently available for use, the band from 5.850 to 5.925 GHz is considered the primary candidate.

The band from 5.850 to 5.925 GHz may become available in the near future from the National Telecommunications and Information Administration (NTIA)[9]. This band is currently allocated to radiolocation (military only), fixed-satellite (earth-to-space), and amateur radio service licensees in the United States and internationally. In addition, it is allocated to fixed and mobile operations internationally. The proposed plan would open the band to non-government use.

Allocating the band from 5.850 to 5.925 GHz to DSRC applications would provide the following advantages:

- There are very few geographical areas where interference would occur while operating in this band;
- The European Standardization Committee CEN TC278 is creating a standard for DSRC from 5.795 to 5.805 GHz, with an alternate of 5.805 to 5.815 GHz [10,11]; and

- Manufacturers in both Europe and the United States are developing DSRC equipment that operates around 5.8 GHz. Expanding DSRC operations to frequencies from 5.850 to 5.925 GHz would create a greater market for 5.8-GHz DSRC products, stimulating sales and research investment, and reducing costs.

To explore the suitability of the 5.850 to 5.925 GHz band in comparison to the 902 to 928 MHz band, the following sections will discuss the types of devices currently available, their signal characteristics, and the environmental effects on communications at these frequencies.

5.2 Device Types and Signal Characteristics

The existing DSRC systems [12][13] in the 902-928 and 5.850-5.925 ranges can be grouped according to their type of vehicle tag and their frequency. Five of the 5.8 GHz systems (including three developed in Europe and two from U.S manufacturers) employ a semi-active tag that modulates a continuous wave (CW) tone from the reader. One DSRC system (developed in the United States) has a 5.8 GHz and a 902 - 928 MHz downlink (roadside-to-vehicle) but uses an active uplink in the 40 - 70 MHz range. The 902 - 928 MHz systems are either completely active with a complete uplink transmitter, or use a reflective type technology in a semi-active or passive tag. The DSRC systems are listed according to frequency and tag type in Table 6.

Table 6. Classes of DSRC Systems

Frequency	In-Vehicle Tag Type	DSRC System
5.8 GHz	Semi-active	Amtech#
	Semi-active	Bosch: MobilPass
	Semi-active	GEC-Marconi: TRICS
	Semi-active	Saab-Combitech: PEMID
	Semi-active	Texas Instruments: EuroPassage#
	Active	AT/Comm*
902 - 928 MHz	Semi-active	Amtech: Intellitag
	Semi-active	Texas Instruments: TIRIS
	Passive	XCI RFID
	Active	Hughes
	Active	Mark IV: RoadCheck
	Active	AT/Comm

New systems - Data not available in appendix A.
* AT/Comm tags transmit in the 40 - 70 MHz band.

The four classes of DSRC systems listed in Table 6 are considered separately in the following environmental analysis. Grouping the systems according to these classes helps simplify the presentation of the results. Specific results from the individual systems will be presented where they differ from the results of the general class of DSRC systems being discussed.

The readers operate with an output power between 20 mW and 10 W EIRP with communications ranges from 15 feet to 1 mile (see Appendix A). The nominal power for operations in the 902 to 928 band is less than 1 W with ranges usually less than 100 feet. However, the Hughes system operates at 10 W EIRP with a two-way range up to 200 feet. AT/Comm uses the broadcast option for its 1 mile range. The power currently in use for operations in the 5.850 to 5.925 GHz band is 2 W with up to a 98 foot (30 meter) range. The range would be slightly extended if 10 W were used. The bandwidth for current DSRC equipment is generally constrained by the FCC requirement on the LMS band to reduce out-of-band signal levels by 55 + 10 log(P) dB, where P is the power of the transmitter. Appendix A of this paper contains updated templates on most of the DSRC systems discussed here.

The following subsections address the relative performance of communications systems for the 902 to 928 MHz band and the 5.850 to 5.925 GHz band.

5.3 Comparative Properties of the Current and Potential DSRC Bands

5.3.1 Antenna Characteristics

Antennas developed for use in the 5.8 to 5.9 GHz band have some advantages over those developed for use in the 902 to 928 MHz band. The primary advantage of the higher frequency antennas is size which is inversely proportional to the frequency. A 5.8 to 5.9 GHz antenna is roughly 1/6 the size of an antenna with similar characteristics in the 902 to 928 MHz band. By giving up some of the size advantage, the higher frequency antennas can be designed to have more narrowly focused beams, reduced sidelobe levels, or both. Therefore, antennas operating in the 5.8 to 5.9 GHz band enhance the ability of the DSRC systems to spatially isolate individual beacons.

A disadvantage of higher frequency antennas is cost. The antennas must be designed and constructed to tighter tolerances in the 5.8 to 5.9 GHz band and are thus more expensive. However, the cost of antennas is a small fraction of the overall cost of the DSRC systems and the additional cost will be almost insignificant.

5.3.2 Propagation Loss

In free space, propagation loss increases as the square of the frequency. Because the ratio of the two bands is about 6, the free space loss at the higher frequency will be approximately 16 dB larger for the same path length. However, for the path lengths encountered in typical DSRC applications, where distances are no more than about 200 meters, the loss at 5.8 GHz is about 94 dB compared with about 78 dB at 915 MHz. Systems can be easily built to function in either band if an ERP of about 40 dBm (10 W) is available.

5.3.3 Active Device Cost

Because of low production quantities and low foundry yields, gallium arsenide (GaAs) devices are currently much more expensive than silicon. However, two factors will reduce the cost of 5.8 GHz devices for ITS. First, the huge market will result in investments in improved foundry processes (as happened with silicon 20 years ago), which will greatly increase the device yield per wafer. Second, at least one microelectronics company has been experimenting with a high-quality "super silicon," which can operate at frequencies up to 6 GHz in the 1 W power range. Assuming that 5.8 GHz transceivers become standard ITS equipment on most vehicles, the cost of the hardware will fall to consumer levels fairly rapidly. Europe has already adopted this band and has initiated experiments in which U.S. manufacturers are participating, so we can expect some cost data to be forthcoming in the near future that will support this opinion.

5. 4 Environmental Effects Analysis

5.4.1 Weather Propagation Effects

The Environmental Analysis Framework and Methodology report [14] (Appendix E) considered the attenuation of fog, rain, snow, dust, and hail at 902-928 MHz and 5.8 GHz. The worst case proved to be heavy rainfall. Viewing several models for atmospheric attenuation due to rainfall demonstrated that the attenuation even for very heavy (100 mm/hr) rainfall produced less than 1 dB/km attenuation. This result was true for both 902-928 MHz and 5.8 GHz frequency bands. Therefore, weather propagation effects will have negligible effects on any of the DSRC systems' propagation.

5.4.1.1 Standing Water

While weather has negligible effect on the atmospheric propagation of the DSRC systems, there is one ancillary effect of rainfall that must be considered. At least one of the DSRC systems (Mark IV) operating at 902-928 MHz uses in-pavement antennas for reading the vehicle tags. During rainfall, the antenna can be covered with standing or running water. This water can cause significant attenuation, especially if the systems were to migrate to the 5.8 GHz band. At 902-928 MHz, the attenuation due to pure water is approximately 15 dB/m and at 5.8 GHz the attenuation is approximately 600 dB/m [15]. Table 7 demonstrates the attenuation of standing water on in-pavement antennas.

Table 7. Attenuation Due to Water on an In-Pavement Antenna

Depth of Water	902-928 MHz	5.8 GHz
0.25 inches	0.1 dB	3.8 dB
0.5 inches	0.2 dB	7.6 dB
1.0 inches	0.4 dB	15 dB
2.0 inches	0.8 dB	30 dB

From Table 7 it can be seen that using an in-pavement antenna at 5.8 GHz would result in significant power losses if water were on the antenna. Excellent drainage would be required to ensure that significant power loss did not occur during heavy rainfall. It would be better to avoid in-pavement antennas at 5.8 GHz in favor of overhead antennas. If in-pavement antennas were required in a 5.8 GHz DSRC system, significant attention would have to be given to power budget in rainfall and drainage around the antenna.

5.4.1.2 Accumulation of Snow on Roadside Antennas

In northern climates, it is possible and often likely that snow will accumulate on or stick to the radomes of the roadside antennas used for DSRC systems. Slick radome materials, heated radomes and antenna designs with vertical faces can reduce or eliminate the accumulation of ice and snow on radomes. If these measures are not implemented, then a layer of snow can accumulate on the face of a radome.

It is assumed that the roadside antennas are either pointing in a downward angle or directly horizontal given the anticipated beacon configuration. It is also assumed that the antenna has a smooth radome such that there are no pockets or cavities in which snow or ice can accumulate. Therefore, the ice on the antenna will be a crust of snow that has partially melted and re-frozen.

Only one example of measurements of attenuation due to crusted snow has been discovered thus far. The Engineering Experiment Station (now known as the Georgia Tech Research Institute) performed measurements on 2 inches of crusted snow at 35 and 95 GHz. [16] The measurements were conducted on dry snow as well as wet snow as the crust began to melt. By extrapolating these measurements and making a few assumptions on the relationship between attenuation and frequency, a rough estimate of the attenuations at 915 MHz and 5.9 GHz can be made.

Wet, crusted snow was found to cause the greatest attenuations in the tests by the Engineering Experiment Station. Extrapolating these measurements results in an estimated attenuation due to 2 inches of crusted snow of about 0.5 dB at 915 MHz and approximately 5 dB at 5.9 GHz. There is a fair margin of error in extrapolating the attenuation based on only two frequency measurements, but the results are fairly obvious. In the 902-928 MHz band, crusted snow on the antenna will not cause and appreciable degradation of the DSRC system's performance. In the 5.850-5.925 GHz band, crusted snow can reduce reflected signal power by about 10 dB (2-way signal loss in reflective tag system). This loss will reduce the maximum operating range of the DSRC system by about 44%. Note that this estimate is crude and further investigation of attenuation due to crusted snow is under way to produce a more reliable estimate of attenuation at the frequencies of interest.

Mitigating snow accumulation can be accomplished using any one or combination of several simple techniques. Since the antennas and radomes are relatively small, a heater can be used to melt the snow. "Slick" materials such as Teflon® can be used to coat the radome to prevent the snow from adhering to the radome. A shield can be placed over the face of the radome to reduce snow accumulation on the face. Also, the antenna can be designed such that the radome face is angled downward. For in-road antennas, the only mitigation method is to keep compacted snow away from the antenna; this may be difficult in some circumstances.

5.4.2 Electromagnetic Environment Effects

The electromagnetic environment effects analysis considered the effects of unintentional emitters, non-DSRC emitters and other DSRC emitters.

5.4.2.1 Unintentional Emitters

The Environmental Analysis Framework and Methodology report [14] demonstrated that the primary unintentional emitter in the DSRC environment was automotive ignition noise. The automotive ignition noise in a typical 6 MHz bandwidth transceiver is well below the sensitivity of the DSRC receivers studied here. Thus, the unintentional emitters are not a significant interference threat to most DSRC systems operating at 902-928 MHz or at 5.8 GHz.

5.4.2.2 Non-DSRC Emitters

Interference sources vary by operational location and frequency. In Denver, CO, non-DSRC emitters in the 902-928 MHz band and the 5.850 to 5.925 GHz band were measured with an omnidirectional antenna. The received signal levels in the 902-928 MHz band were about -88 dBm (adjusted for a 600 kHz bandwidth and an isotropic antenna). Other measurements made at 5.250-5.925 GHz also in the Denver area show a received signal level of about -92 dBm (adjusted for a 600 kHz bandwidth and an isotropic antenna). However, the signal level would have been much lower if a directional antenna had been used. This type of measurement was done for non-DSRC emitters in the 902-928 MHz band and the 5.850 to 5.925 GHz band in the Frequency Spectrum Survey conducted for the Florida Department of Transportation, dated 1994. This survey was conducted with log-periodic directional antennas which have characteristics similar to some DSRC antennas. It was found that most of the measured sites had strong signals near or in the 902-928 MHz band and none had strong signals in or near the 5.850 to 5.925 GHz band. The average peak signal strength among the locations measured in the 902-928 MHz band was -58.56 dBm. The strongest of these signals in the 902-928 MHz band was -41dbm at 908.37 MHz. Many of the DSRC systems use the range between -30 and -60 dBm as the receiver sensitivity for the tag or reader or both. Most of the sites measured in the 5.850 to 5.925 GHz band had readings better than -100 dBm and only 16 of the 30 sites had a measurable signal in the band. This data means that 5.850 to 5.925 GHz band is a much better operating environment than the 902-928 MHz band.

5.4.2.2.1 Interference Sources in the 902-928 MHz Band

The DSRC systems operating in the 902-928 MHz band include both licensed and unlicensed (Part 15) roadside readers (all tags are unlicensed). Figure 23 shows the currently licensed operations in the 902-928 MHz band. Those systems operating in an unlicensed mode are not protected at all against other interference sources. The short range nature of the DSRC systems do offer some protection and some of the systems even use a squelch to reduce interference from other emitters operating in the band. Unfortunately, the 902-928 MHz band is quickly becoming popular for a number of unlicensed emitters including new cordless telephones.

The only DSRC system that boasts an unlicensed (Part 15) roadside reader is the XCI Radio Frequency Identification (RFID) system. This system uses a distinctive RF chirp signal to help differentiate valid in-vehicle tag responses from background noise.

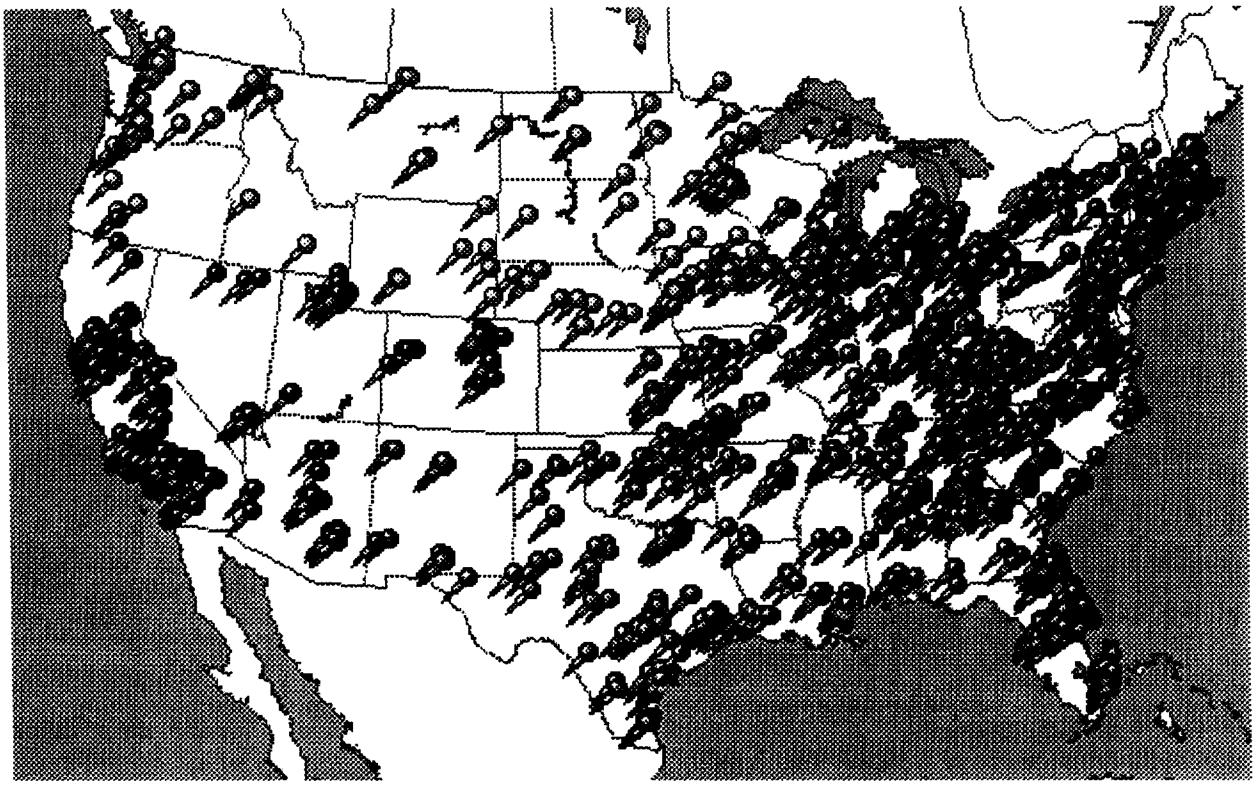

Figure 23. Emitters Licensed in the 902 - 928 MHz Band

The remaining 902-928 MHz DSRC systems require licensing of the roadside readers under FCC Part 90. This offers some protection against interference sources. Other licensed systems are required to coordinate with the DSRC system to avoid interference. Part 15 devices, however, can still operate in and around the operating band of the licensed DSRC system. These can affect the in-vehicle tag and the roadside reader if operated in close proximity. Fortunately, most Part 15 devices are not operated in a mobile environment, but are instead operated in the home or business environment.

5.4.2.2.2 Interference Sources Outside the 902-928 MHz Band

A major source of interference for DSRC systems operating in the 902-928 MHz band comes from emitters outside the band itself. Figure 24 shows the currently licensed operators in and around the 902-928 MHz band.

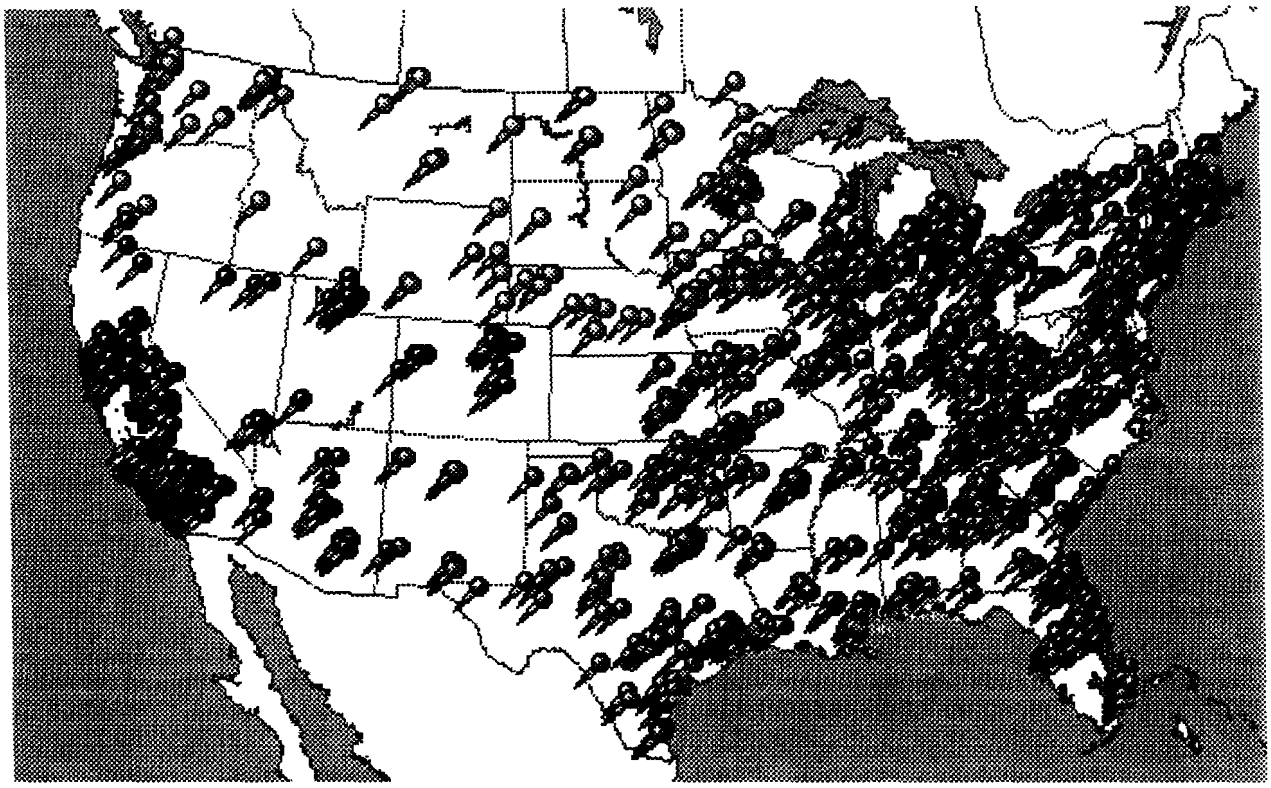

Figure 24. Emitters Licensed In and Around the 902 - 928 MHz Band

In-vehicle tags are typically inexpensive devices that often operate on small batteries. These inexpensive devices have a fairly wide bandwidth and simple front end filtering which leaves them vulnerable to strong emitters in nearby frequency bands. The interference typically does not interrupt communications, but rather causes the tag to activate unnecessarily and waste energy. Repeated activation of the tag can reduce battery life. [17]

Field testing has shown that the emitters which can cause the tag to activate include passing mobile telephones, AMPS cellular phone base stations, fixed pager base stations and UHF television stations. When tags are near these sources, the field strength can exceed the threshold and activate the tag and waste energy. In its inactive or sleep mode, the tag uses only 1 to 2 microamperes. When activated or awakened the tag uses several milliamperes of current. Therefore the incidental activation of the tags due to other non-DSRC emitters can cause a serious drain on the batteries. [17]

To mitigate the effects of the non-DSRC emitters near the band of operation of the tags, some tags use a 3-stage system. Normally the tag is in the sleep mode, drawing 1 to 2 microamperes, and monitors a simple passive field strength detector. When the detector output exceeds a pre-set threshold, the tag enters a "lookaround" mode wherein it examines the field for the characteristics of a beacon while only drawing a few more microamperes. The wakeup mode, which draws several milliamperes, is only entered if the tag has determined that the signal is from a beacon. This strategy conserves considerable battery life that would otherwise be lost to the out-of-band emitters. [17]

5.4.2.2.3 Interference Source In and Near the 5.850 to 5.925 GHz Bands

In this section, the potential source of interference in and near the 5.850 - 5.925 GHz band will be assessed. Measurement of background emission in the Denver, Colorado area showed a noise level in the 5.250-5.925 GHz band of less than -92 dBm (adjusted for a 600 kHz bandwidth and an isotropic antenna). In the 5.795-5.805 GHz, band used by the European systems (Bosch and GEC-Marconi), a signal with a -75 dBm power level was detected. In the 5.850-5.925 GHz band being considered for U.S. DSRC systems, no strong signals were detected. These background noise levels measured in Denver pose little or no threat to the DSRC systems studied in this effort. If licensing for U.S. DSRC systems in the 5.850-5.925 GHz band is approved (co-primary status with earth-to-satellite links), considerable protection for the operation of the DSRC systems can be achieved. Coordination with the earth-to-satellite links does not appear to be a problem at this time. [18]

It is assumed that the DSRC systems operating in the 5.8 GHz band will be wide bandwidth devices using a reflective or backscatter technology. They will likely be fairly inexpensive devices. Therefore, it is likely that these tags will also be vulnerable to activation and interference from source outside its operating band as well as those inside the band.

The primary non-governmental use of the 5.850-5.925 GHz band is for fixed satellite earth-to-space links. Figure 25 shows the current licensed earth-to-satellite fixed stations in the 5.850-5.935 GHz band. There are currently only 8 licenses in the contiguous United States in this band.

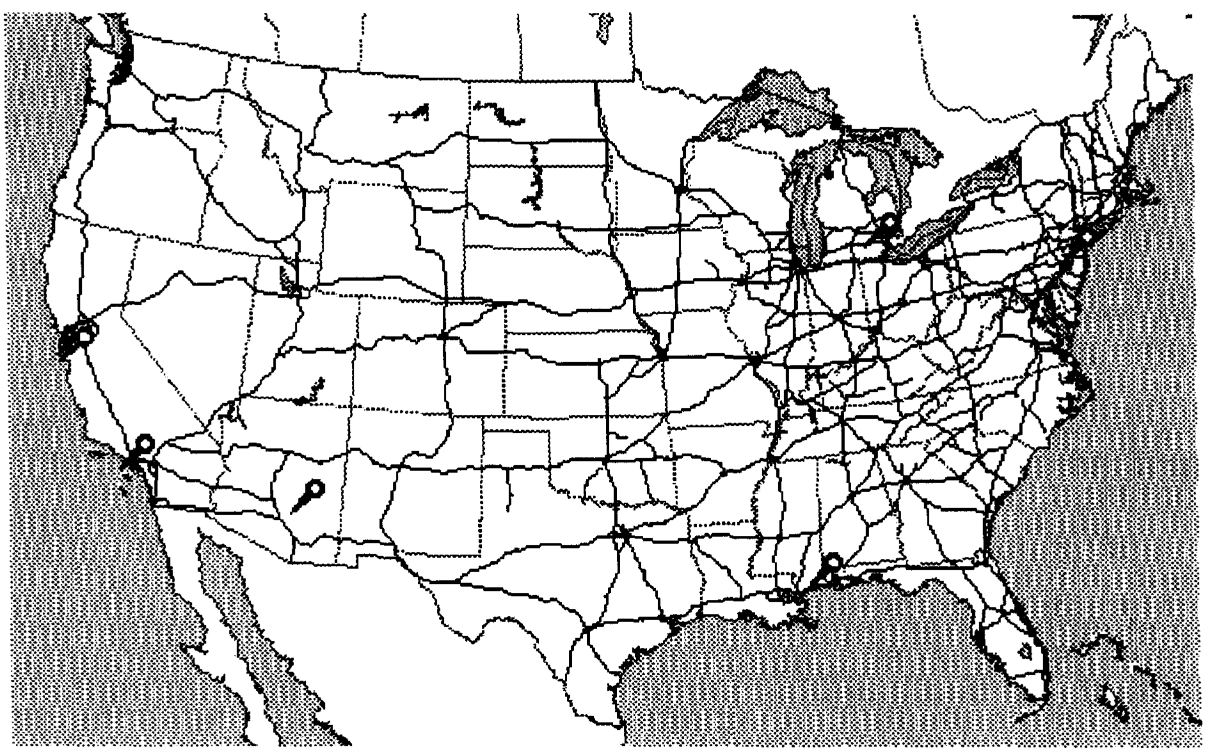

Figure 25. Emitters Licensed In the 5.850 - 5.925 GHz Band

There are two primary reasons to conclude that in-band emitters will not be a problem for DSRC systems operating in the 5.850 - 5.925 GHz bands. First, there are very few of these emitters, and thus mitigation would simply consist of avoiding beacon installations close to one of these emitters. Second, these are all earth-to-space satellite links using high-gain, low sidelobe antennas that point up, away from Earth. These emitters use low sidelobe antennas to avoid interference with other satellites, and thus will also reduce drastically the interference with DSRC systems. Conversely, DSRC systems will also not interfere with the satellite communications since these are uplinks to the satellites and the radiated power levels of DSRC systems will not significantly impact a satellite receiver.

The interference potential rises dramatically when emitters in bands adjacent to the 5.850-5.925 GHz bands are also considered. The 5.650-5.850 GHz band is a Radio Location and Amateur band. Some high power weather and tracking radars exist in this band. But, generally transmitted power levels are typically low to moderate. There is also a 5.725-5.875 GHz ISM band which overlaps with the 5.850-5.925 GHz band. Note, however, that the current 902-928 MHz systems operate in an ISM band with currently manageable interference problems.

The 5.925-7.075 GHz band is the potentially most serious source of interference problems. This band is used for earth-to-space fixed communications, but is also used for public and private fixed communications links. These fixed communications links can operate at high powers and over considerably long distances. A quick scan of the current licenses in this band reveal transmitter power levels exceeding 3 kW.

The scope of the interference problems from emitters in and near the 5.850-5.925 GHz band is demonstrated in Figure 24, which depicts the locations of all emitters whose license includes frequencies in or up to the edges of the 5.850-5.925 GHz bands. There are a large number of these emitters, mostly concentrated around urban areas where most DSRC emitters will be deployed.

Several mitigating techniques will be required to reduce the effects of the emitters in bands adjacent to the 5.850-5.925 GHz band on in-vehicle tags. A multi-stage tag wake-up scheme will likely be required to reduce the drain on battery life from activation due to these emitters. The implementation of this technique can be similar to those currently employed in tags in the 902-928 MHz band. Despite the number of emitters shown in Figure 26, the problem of battery drain is less significant when operating near 5.8 Ghz, because there are fewer potential interfering emitters operating near 5.8 GHz than there are cellular telephone and pager base stations in the 902-928 MHz band.

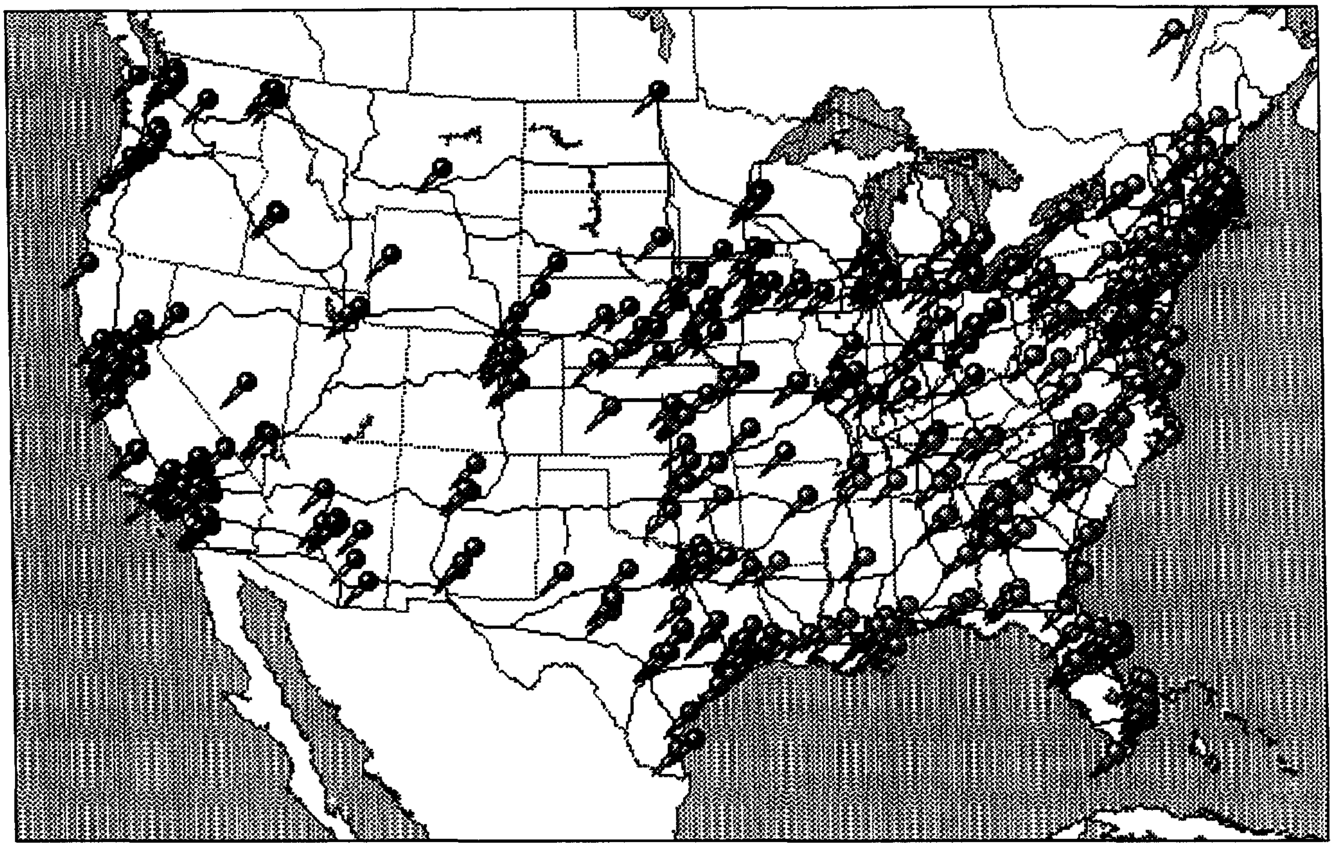

Figure 26. All Licensed Emitters In or Adjacent to the 5.850-5.925 GHz Band

A multi-stage wake-up scheme will conserve battery life, but may not completely solve the interference problems. Given the high transmit power levels of some of the fixed links, they may be capable of blocking communications between the beacon and the in-vehicle tag. The wide-band, simple detector front ends can be saturated by any strong signal that is not filtered out. Therefore, increased filtering is required to reduce the impact of the strong out-of-band signals. To provide this sharp filtering, a guard band near 5.925 GHz can be used. Providing 1 to 6 MHz of bandwidth to implement a sharp, deep filter can virtually eliminate the interference from emitters above 5.925 GHz. The bandwidth of the guard band and the depth of the filtering required to mitigate interference from the emitters above 5.925 GHz depends on cost and the power levels of the interference. Simple tests of field intensities around the interfering emitters are needed to determine the extent of filtering requirements to mitigate interference.

Potential interference sources below 5.850 GHz typically transmit at much lower power levels than those above 5.925 GHz. Therefore, filtering these signals out of the input to the tag receiver is not as difficult. A smaller guard band or a less complex filter is needed to mitigate interference from emitters below 5.850 GHz.

5.4.2.2.4 Other DSRC System Emitters

The potential for interference from other DSRC emitters is a recognized problem. The manufacturers of DSRC systems, particularly Electronic Toll Collection (ETC) systems, have had to implement solutions to interference problems between adjacent lanes. These techniques require cooperation or coordination between the roadside readers; some require discrimination by the in-vehicle tag. The following are examples of the techniques to avoid lane-to-lane interference used by the DSRC systems studied:

- The AT/Comm system uses an FM capture technique, and claims to provide orderly sequencing of multiple messages from the vehicle tags. The FM capture technique differentiates by the power levels of the received signals, communicating with the tag with the highest power level first.

- The Bosch MobilPass and Saab-Combitech systems use TDMA for multiple access. The typical configuration uses one reader per lane with tight antenna beams and low power levels to avoid interference.

- The Hughes DSRC system coordinates the communications times of adjacent or nearby readers to avoid cross-talk between communications zones.

- The Intellitag system uses directive antennas and power control to avoid cross-talk between lanes or communications zones. Time division is also used to reduce cross-talk between adjacent lanes in an ETC application. Furthermore, the system has the capability of employing frequency discrimination between lanes, varying the reader frequency between lanes, to augment the reduction in interference.

- The GEC-Marconi TRICS system also uses directive antennas and power control to avoid interference between lanes or communication zones.

- The Mark IV system also uses directive antennas and power control to avoid interference between lanes or communication zones. In addition, time division is used to reduce cross-talk between adjacent lanes in an ETC application.

- The Texas Instruments TIRIS system uses time delayed pulses from the individual lane readers to allow the in-vehicle tag to determine the lane it is in. The amplitudes of the pulses are compared at the tag and the highest amplitude pulse is determined. The tag then only responds to queries from the lane whose pulse had the highest amplitude.

- The XCI RFID system uses extremely low power levels and directive antennas to discriminate between lanes. They claim very little problem with cross-talk that the programmable readers cannot correct.

Along with the interference rejection methods described above, many of the single-lane implementations of the DSRC systems also use vehicle detectors to determine the presence of a vehicle. Only when a vehicle is present will the reader attempt to communicate with the in-vehicle tag. This reduces the amount of cross-talk between lanes and improves the enforcement capabilities of the toll and access control systems.

Given that the designs of the DSRC systems have included measures to reduce cross-talk between adjacent roadside readers in the same DSRC system, it is obvious that adjacent DSRC systems would require similar coordination in order to avoid interference between the DSRC systems. For example, a DSRC system employed to collect tolls at the exit of a toll road may get interference from a nearby DSRC system set up for parking access control or automatic fee payment.

Frequency separation between nearby DSRC systems is not sufficient to control interference. The reflective and backscatter techniques used by most of these systems are designed to automatically adjust their response to the frequency of the reader. If two reader signals at the same or different frequencies are received from different DSRC systems, the response of the tag may be unpredictable and unreliable. Time division or spatial techniques must be employed to reduce the interference problems between nearby DSRC systems.

Active in-vehicle tags can be used to respond to individual reader frequencies. The cost of producing active systems capable of responding to multiple frequencies (channelized receivers) may be prohibitive. Therefore, the solution to interference between adjacent DSRC systems is time or spatial differentiation. Active systems can, however, be used to differentiate a particular frequency. An example of this would be a dedicated emergency or safety channel.

The problem of interference from other nearby DSRC systems is perhaps the most significant problem yet to be completely solved. The problems get worse if DSRC systems are employed using multi-lane beacons instead of the single lane readers currently used by ETC systems. Mitigation analysis is required to resolve this problem.

5.4.3 Physical Effects

The physical effects on the DSRC systems include blockage (or diffraction) and multipath. The Environmental Analysis Framework and Methodology report [14] considered each of these effects and presented theoretical results for analyzing particular geometries associated with DSRC communications. These effects are discussed below to determine the extent to which the physical effects cause degradation of the DSRC systems.

5.4.3.1 Blockage / Diffraction

The diffraction analysis in the methodology report demonstrated that blockage causes significant losses in received signal power. Using a knife-edge approximation for a blockage, the analysis also showed that the effects were significantly greater at 5.8 GHz than at 915 MHz. Both frequency bands basically require line-of-sight between the roadside reader antenna and the in-vehicle tag.

A typical ETC application where individual antennas are used in each lane of traffic virtually eliminates blockage problems. A standard ETC installation uses an antenna mounted 16 feet off the roadway and pointed 30 degrees from vertical toward oncoming traffic. In this configuration, a car (tag 3 feet off the ground) would have to follow a 12 foot tall truck such that the tag is less than 5.5 feet from the back of the truck to be affected by blockage. This is an unlikely scenario. Another analysis [19] showed that blockage from roadside-mounted DSRC antennas can be significantly reduced by using multiple antennas (one on each side of the road).

Diffraction or blockage must be considered in the design and layout of DSRC systems. Antenna positioning and direction must be carefully designed to reduce the likelihood that blockage could occur. Blockage would prevent communications between the roadside reader and the in-vehicle tag in many cases.

Blockage is a site-specific and implementation-dependent problem. It has been considered in the design of existing DSRC systems, and, for the most part, has been resolved. Therefore, further consideration of this problem is not warranted for the current environmental analysis of DSRC systems.

5.4.3.2 Multipath

Multipath is a problem that has generally been addressed in the design of the DSRC systems tested. Most of the ETC applications use a protocol that includes acknowledgment to ensure the reliability of the link. Also, all of the systems generally communicate in short bursts, generally much shorter than the time between fades. At 5.8 GHz, the interval between fades is 0.158 the interval between fades at 915 MHz. [14] This means that fades occur more often and thus there is a greater chance that a fade will occur during a transmission. The other side of the coin is that the duration of the fades at 5.8 GHz is also 0.158 as long as at 915 MHz. Thus fewer bits are disrupted per fade at 5.8 GHz.

For ETC and access applications, the acknowledgment protocols currently implemented are sufficient to ensure very good reliability on the communications channel. Most of the systems are designed to allow for three chances to communicate with each passing vehicle in case a fade occurs. For other DSRC applications requiring longer messages, a TDMA system with acknowledgments can ensure nearly the same accuracy as the ETC systems.

Some design techniques can and have been used to minimize the effects of multipath on DSRC systems. High gain, low sidelobe roadside antennas minimize the reflection problem. The roadside reader antenna angle can also be adjusted to minimize the reflectivity of the environment. The high dynamic range front end can be designed into the roadside reader to minimize the effects of fading by allowing the receiver to track through most fades. Also, transmitter power levels can be adjusted to swamp the nulls, but consideration of cross-talk between lanes must be considered. [17]

Multipath is a problem with any mobile communications system. It has, however, been addressed in the design of most DSRC systems. While some problems do exist in multipath, most can be addressed using design and implementation strategies. The acknowledgment protocols currently being used can prevent a great percentage of the errors introduced by multipath. Therefore, further consideration of the multipath environment is not necessary at this time.

5.4.4 Environmental Effects Summary

A review of the environmental effects on DSRC systems has shown that the most significant problem is likely to be interference from other DSRC systems. This problem has already been addressed to resolve lane-to-lane interference issues within a single DSRC system. It has not been strongly addressed for the case of multiple DSRC systems operating in close proximity.

Interference from non-DSRC systems is currently not a significant problem. The growth of unlicensed (Part 15) devices may, however, be a problem in the 902-928 MHz band in the near future. If co-primary status with earth-to-satellite transmitters is granted to DSRC systems in the 5.850-5.925 GHz band by the FCC, greater protection of the DSRC communications can be provided. Interference between the very localized DSRC transmissions and the very directive earth-to-satellite links should pose little problem. It must, however, be considered in the granting of licenses as DSRC systems are deployed.

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6.0 ANALYSIS OF THE 5.850 TO 5.925 GHz BAND USE

6.1 Other Users of the Band

As stated previously, the 5.850 to 5.925 GHz band is currently allocated to radiolocation (military), fixed-satellite (earth-to-space), and amateur in the United States and internationally. However, when the band is released to commercial use, primary status will probably be assigned to users other than military radiolocation. Furthermore, reports and studies of the radiators in and around this band indicate that the band is generally low in background emissions with the main source of possible interference to DSRC systems being out-of-band radar emissions.· Most of the information in this section comes from the study, "Technical Evaluation of the 2.45 and 5.8 GHz ISM Bands for Intelligent Vehicle Highway Systems," A.D. Spaulding [18] and the report, "NTIA REPORT 93-294 Federal Government Spectrum Usage in the 902-928, 2400-2500 and 5725-5875 MHz Bands," U.S. Department of Commerce/NTIA, February 1993 [20]. Some of the possible sources, mentioned in the reference documents, include the following radars, which operate just below the band, but whose emissions may impinge on the band:

RADAR MODEL	FREQUENCY (MHz)	PEAK POWER (kW)
WSR-74C and AN/FPQ-21	5450-5825	250
DWSR-88C,-88TVand-90CTV	5450-5825	250
AN/FPQ-10	5725-5875	285
AN/FPS-16	5400-5900	5000
AN/FPS-105	5725-5875	1000
AN/FPS-105	5725-5875	1000
AN/MPS-25	5725-5875	1000
AN/MPS-26	5725-5875	250
AN/MPS-36	5725-5875	1000
AN/TPQ-18	5725-5875	2800
AN/TPQ-39	5450-5825	250
MOT MRS 111	5725-5875	0.4
VEGA 6571	5725-5875	1000
VEGA 6572	5725-5875	1.5
VEGA 6104	5725-5875	3.5
VIVRIR778	5725-5875	1000

Also included in the possible interference sources for this band is the INTELSAT satellite uplink transmission system. Twelve assignments relative to the INTELSAT system are currently registered. This equipment has the following characteristics:

TRANSMITTER	FREQUENCY (MHz)	AVG POWER (kW)
INTELSAT VI Earth station	5850-5875	1

The INTELSAT ground station transmitters radiate upward at relatively low power levels compared to most of the radars. Little interference is expected except in the immediate vicinity of the station.

Most of the transmitters in this range are government tracking radars or weather radars. The tracking radars operate mostly on remote ranges, and therefore have little influence on main highways. Weather radars are few in number but are scattered across the country at airports and other locations. Furthermore, the number of government meteorological radar stations in the vicinity of 5600-5650 MHz is expected to decline by approximately 60% by 1997 because the National Weather Service WSR-74S and WSR-74C radars are being replaced by the NEXRAD radar at 2700-2900 MHz. Measurements of the WSR-74S radar indicate a signal level of less than -90 dBm in the 5.850 to 5.950 GHz range, which is compatible with DSRC operations, at a distance of 1/2 mile. However, measurements of the WSR-74C radar show between -40 and -60 dBm in the 5.850 to 5.950 GHz range, which is not compatible with DSRC operations, at 1-1/2 miles distance. Fortunately, measurements of the NEXRAD radar show less than -80 dBm in the 5.850 to 5.950 GHz range, which is again compatible with DSRC operations, at 1/2 mile. And synthesized spectrum analysis [18] of the Terminal Doppler Weather Radar (TDWR) shows less than -85 dBm in the 5.850 to 5.950 GHz range, which is also compatible with DSRC operations. Operating ranges and power levels of the radars compatible with DSRC are listed below:

RADAR MODEL	FREQUENCY (MHz)	PEAK POWER (kW)
WSR-74S	2700-2900	500
NEXRAD	2700-2900	250
TDWR	5600-5650	250

The DWSR-88TV and DWSR-90CTV Doppler radars, which are not directly compatible with DSRC operations, will be increasing in number from 1995 to 1997. Analysis of the DWSR-88TV radar potential interference indicates that, if the radar is operating at the proper frequency, a separation distance of seven miles is required to prevent interference to DSRC equipment in an ideal propagation environment. Fortunately, few of these radars are or will be deployed in comparison to the vast size of the national roadway structure, and the effect of hills, buildings and other obstacles will limit the interference of the ones that are within range of a road.

6.2 Coexistence Plan

Almost all of the nation's roadways will be free of interference to DSRC in the 5.850 to 5.925 band. In those small pockets where either weather radars or satellite stations have the potential for interference, DSRC installation design adaptations should be implemented to compensate for the unwanted signals. These adaptations could include installing highly directional antennas, filters, and signal absorption or reflection devices. The DSRC operations are low power and pointed down toward the roadway or horizontal to the roadway. Therefore, the DSRC operations are not expected to interfere with weather radar operations. The INTELSAT operations are earth-to-space uplinks so they have no receiver for DSRC operations to influence. In the 5.850 to 5.925 band, individual installation frequency allocations for the eight DSRC channels can be moved around to avoid spurious out-of-band radar, INTELSAT operations, and other transmission peaks. The lower 25 MHz of the band contains some ISM band activity, INTELSAT and radar activity which could be avoided by using the middle part of the band for DSRC where necessary. Also, the upper 6 MHz of the band could be used as a guard band between the high-power operations just above 5.925. Therefore, since this room can be used to facilitate sharing the band with other services, the full 75 MHz in the band should be allocated to TIRS for the DSRC function in a co-primary status with earth-to-space satellite communications.

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7.0 BAND UTILIZATION CONCLUSIONS

7.1 Protection of the Legacy Band at 902 to 928 MHz

As stated above, most DSRC and RFID equipment in the U.S. currently operate in the LMS band. The ETC, CVO, and intermodal freight management applications are currently implemented in this band, and implementation of parking payments is underway.

The LMS band is important to the ETC and CVO applications because the investment of capital already made in deployment must be protected so that the industry can grow and provide the full benefit of these services. Some installations have been in operation for a few years. Many other installations are just coming on line or are in the planning stages. The public is just beginning to notice the benefit of this technology. A substantial effort is being made to sell the current systems and expand the market before spending more money to change the frequency of operation. Although, changing will bring the benefit of a more protected band and is planned to enable interoperability between applications some time will be needed for these applications to migrate to 5.850 to 5.925 GHz.

The LMS band is important to the AEI applications also, because an even more substantial amount of deployment has occurred. These tags are being manufactured in large numbers, representing a sizable base of effective equipment that will not need total replacement for many years. They are being used in the transportation industry to identify rail cars, shipping containers, trailers, shipping crates, boxes, and other objects whose handling is expedited by remote identification. In addition, a significant propagation advantage exists for AEI applications in the 902 to 928 MHz band that is difficult to achieve in the 5.850 to 5.925 MHz band. There is less attenuation from "shadowing," or partial blockage of the propagation path between the reader and tag, in the lower frequency band than in the 5.850 to 5.925 band. Some AEI applications, unlike ETC applications, must identify objects that are always partially masked by other objects. The higher band is hence not an attractive option for AEI applications where such shadowing may occur.

For these reasons, the AEI applications are not expected to transition from 902 to 928 MHz to another frequency range. Therefore, this band must maintain its LMS allocation for the foreseeable future.

ETC, parking, and CVO users, also, need the option to operate in this band for a substantial time. It is expected that these users will migrate to the 5.850 to 5.925 band when they are economically ready.

7.2 Operations in the 5.850 to 5.925 GHz Band

The currently allocated LMS band does not have the bandwidth or authorization for operation that will allow all DSRC functions to be effectively implemented. The new applications (In-Vehicle Signing [Hazard Warning], Emergency Vehicle Signal Preemption, Transit Vehicle